Modeling and Validating the Effects of
Sound on the Marine Environment

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LONG-TERM GOALS

The long-term goals are to develop novel techniques to measure and predict, through modeling, the effect of sound on the marine environment. Modeling includes acoustic sources, propagation and the interaction of sound with animal behavior models. Determining the necessary environmental information such as bathymetry, sound speed and seabed properties for accurate modeling is also an essential component of this work.

OBJECTIVES

The objective of this research is to develop accurate and efficient modeling tools for estimating the impact of sound on marine life. The goal is to provide state-of-the-art, open source codes to model sound sources, sound propagation and animal behavior. We are also assembling open source environmental databases for quantities such as seabed properties, bathymetry and ocean sound speed. Together, these tools will provide the best estimate of the impact of various sonar systems on the marine environment. These tools are bundled with a simple user interface called the One Navy Model (ONM) for Acoustic Effects Software (formerly known as the Effect of Sound on the Marine Environment (ESME) Workbench). This is intended to be a type of gold standard for estimating impact. Currently, Navy environmental impact statements are prepared at the Naval Undersea Warfare Center (NUWC) and by several government contractors. The software and databases being used are often either classified or proprietary. ONR has put together a team consisting Boston University (David Mountain), Biomimetica (Dorian Houser), HLS Research (Michael Porter) and Portland State University (Martin Siderius) to build software, which will make the needed calculations for assessing environmental impact without using classified or proprietary components. During this project, in 2009-2010, there were three main areas of research, 1) Quantifying and comparing different methods for modeling sonar impact, 2) Validation and verification of the propagation modeling algorithms 3) Developing an Adaptive Mesh Refinement (AMR) algorithm to more quickly assess marine mammal harassments in large volumes of ocean.

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APPROACH

Comparison of current methodologies for preparing impact statements
A study was conducted to compare two methodologies for incorporating marine animals into environmental impact calculations and demonstrate the differences between them. In short, marine mammal impact is estimated by calculating the expected sound pressure level and the animal distributions. Two methods for animal distributions are considered, the first assumes the animals are distributed in depth according to a species dependent histogram. This is a static approach in that it treats the animals as frozen in time at depths corresponding to the histogram. The second method uses simulated animals (animats), which are randomly distributed in an area of interest and their swimming behavior is simulated over time. The static distribution method accounts for a species location in depth by assuming a particular diving behavior for the species. The animal's statistical distribution in depth is generally derived from collected data or using a data-driven animal movement model such as Biomemetica's 3MB [1]. This method contains no time dependence and therefore assumes the mammals remain within sub-volumes of the simulation space.

Comparisons between the animat and static distribution methods were made based on a generalized, range-independent environment, which allowed us to study the effects the methodologies without excessively complex environments. The ray/beam code Bellhop [2,3] was used as the acoustic propagation model with the environmental parameters dependent on the specific scenario. A shallow diving and deep diving species were simulated in both shallow and deep ocean environments. For simplicity, the modeling and discussion was limited to Level B harassment due to behavioral disruption and in the absence of auditory fatigue. The number of harassments estimated to occur from an exercise involving mid-frequency sources was calculated by evaluating a risk function that relates the risk of harassment to the maximum sound pressure level (SPL). The risk function varies between 0 (no risk) and 1 (maximum risk) and can be interpreted as the proportion of the time a given individual may alter its behavior in response to a given max SPL [4]. This value was then extrapolated to the population level to give the number of takes in each method.

The study concluded that the two methods do not produce the same result because the static distribution method is not time-dependent. Removal of the temporal component eliminates the potential for an animal to occupy more than one sub-volume and reduces the risk of encountering higher-level exposures. Intuitively, this becomes clear if one considers a sound source that ensonifies a small region with an SPL near 195 dB for a very long period of time. The animat method would reveal that (given enough time) eventually *all* of the marine mammals would pass through this high intensity region and be harassed. The static distribution method, on the other hand, would arrive at a smaller, fixed number of harassments based only on the typical volume distribution of the marine mammals.

Approach to Adaptive Mesh Refinement of the simulation space
Often, underwater sound activity includes a number of sources at different frequencies possibly moving on different platforms (e.g. ships) for several hours or days. Calculating the expected SPL for these types of scenarios creates a significant computational burden. The need to run faster simulations motivates us to review some of the underlying analysis assumptions and techniques to see if improvements in efficiency can be achieved.

The Level B non-physiological takes threshold accounts for the impacts on marine mammal behaviors (feeding, mating and nursing, etc.) in the proximity of acoustic activity. These takes or "harassments" are computed using a risk function based on maximum received sound pressure levels (SPL). For a

given SPL (above 120 dB re: 1μPa) the risk function is used to estimate the number mammals that will be taken within a given species population [4]. The risk function for odontocetes is plotted in Figure 1A.

A   B
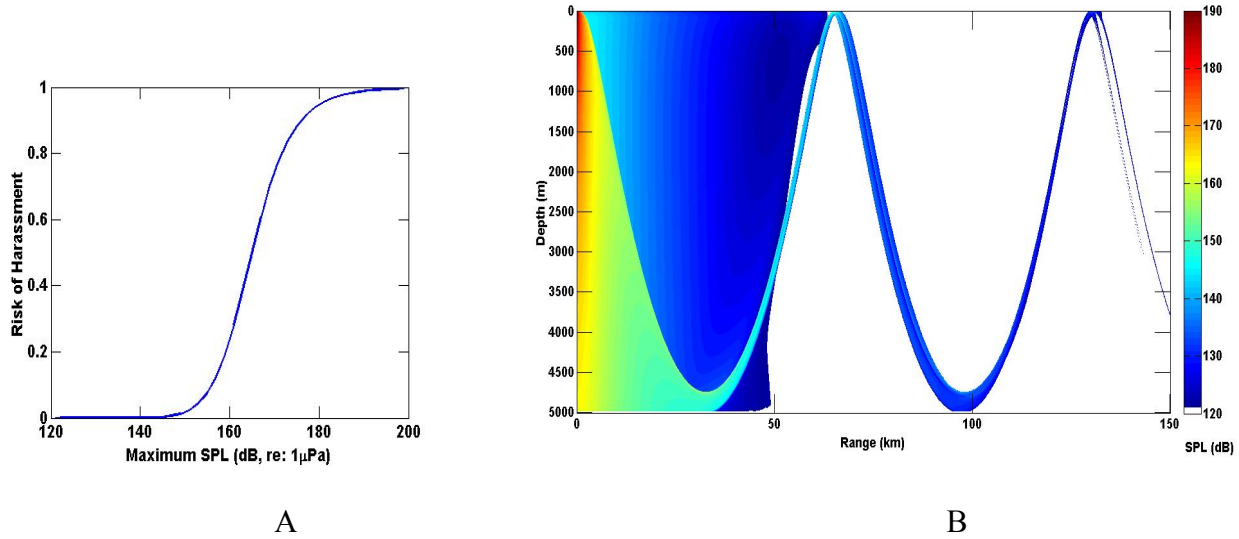
Figure 1. Panel A: The risk function indicates the proportion of a population that is expected to alter its behavior in response to a given maximum SPL. Panel B: Deep ocean SPL values calculated with uniform 5 meter grid spacing. SPL below the basement level of the risk function (120 dB) are not shown. Intensity changes rapidly in some regions near the source and convergence zones, while other relatively large regions have very low intensity levels.

For typical sound sources used in the ocean the SPL may not reach the risk function minimum 120 dB level (representing zero risk) for many kilometers. For this study we consider a typical narrow-band acoustic source at a depth of 10 meters below the ocean surface. The source is omni-directional and emits a single "ping" at a frequency of 3 kHz with intensity of 235 dB relative to 1 micro-Pascal. The water column has a typical deep-water sound speed profile ("Munk" profile), extending from the surface to a depth of 5000 meters [5]. To minimize the number of variables we assume the ocean surface is perfectly calm and the bathymetry is flat, so that the entire volume can be represented by a single range-depth transect. The seabed is assumed to be a silty-sand with sound speed of 1550 m/s, density of 1.5 g/cm^3 and attenuation factor of 0.2 dB/wavelength. Figure 1B shows the SPL values calculated using the propagation model Bellhop [2,3] with uniform 5 meter grid spacing. SPL levels below the basement level of the risk function (120 dB) are not shown.

Thus, the combination of the 120 dB low end of the risk function with the source level of many underwater sound sources requires propagation modeling over vast regions of the ocean volume. In addition, we note that the intensity changes rapidly in some regions near the source and convergence zones, while other relatively large regions have very low intensity levels. The AMR method is well-suited to quickly solve such problems which require varying levels of resolution [6]. The AMR technique results in patches of refined grids, which are then joined together into larger coarsely sampled grids through interpolation. Therefore, the AMR method allows us to more quickly establish

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the risk at all points surrounding the sound source. Basing the AMR grid refinement regions on the risk (as opposed to the intensity) allows us to determine the optimal sampling dimensions for the simulation space.

Multiplying the risk by the population distribution provides the number of taken mammals at each point in the simulations space. Evaluation of the total number of takes then provides a metric for comparison of the AMR method with the conventional uniform grid approach. Marine mammals often swim in pods, but for simplicity we will assume them to be distributed uniformly across the ocean's surface with a density of 0.5 mammals/km^2. This density is higher than what is typically observed, but will be used to make the number of takes more meaningful for this simple scenario. Marine mammals may spend a majority of the time near the surface and exhibit a variety of diving behaviors, which are unique for each species, but in this example we will assume them to have a uniform distribution in depth down to 2000 meters. Ultimately, this reduced simulation space may be used to run simulations in which movements of simulated animals (animats) can be incorporated for additional accuracy in time-dependent analyses, but these assumptions help generalize and simplify the scenario and more easily compare the two analysis methods.

A closer inspection of the number of takes can also provide a more appropriate boundary for the simulation space. This allows us to determine the maximum extent of the modeled region, with the potential error quantified in terms of marine mammals. We find that the maximum range required for a simulation may be reduced from what would be required by the 120 dB minimum of the risk function.

Approach to ONM Software Validation and Verification
The ONM contains code written by programmers at Boston University. The software will ultimately serve as an open source code, which can be easily learned and used by the scientific research community. The ONM has recently reached a level of maturity where it can be thoroughly tested by new users. The purpose of the testing is to put the tools to use in a variety of simulation environments and to identify programming errors as well as to offer suggestions for improving the user interface. A series of test cases are being developed by the Portland State team to both insure the code produces correct results but also to provide users with a set of training examples.

WORK COMPLETED

Work completed on comparison of current methodologies for preparing impact statements
We completed a series of simulation studies to compare the different animal distribution methods for computing EIS's. The studies held all parameters constant except we changed the calculation of number of harassments depending on whether the static distribution method or animat methods were used. The results were published in the Marine Environmental Research Journal.

Work Completed on Adaptive Mesh Refinement of the simulation space
We completed a series of simulation studies to compare the conventional uniform grid method with the AMR method in the range and depth dimensions. The studies held all sound propagation parameters constant and compared the processing time and number of harassments resulting from each gridding method. The number of takes as a function of range was also evaluated. An algorithm to execute the AMR method in the bearing dimension has been outlined, including an automated procedure to ensure that important features in the bathymetry are included in the simulation. Results are shown in the

results section. The results were presented at the IEEE Oceans conference, and a paper was published in the conference proceedings.

Work Completed on One Navy Model Software Validation and Verification

The ONM software was installed at the Northwest Electromagnetics and Acoustics Research (NEAR) Lab at Portland State University. Users loaded simulation environments and ran transmission loss (TL) calculations for a variety of scenarios and made notes of errors and/or suggestions for improving the software. In addition, one of the research assistants validated the propagation modeling sub-routines by reproducing similar programming steps in MATLAB. In the process he was able to (1) verify the implementation of acoustic propagation algorithms and (2) validate that the algorithms were coded correctly (3) develop a test scenario that can be provided to new ONM users.

RESULTS

Results on comparison of current methodologies for preparing impact statements

Many different scenarios can be contrived by varying the environments, changing source parameters and considering multiple species but some typical cases have been selected for illustrating the results. A simple example can be used to illustrate the differences between the static distribution and animat analysis methods. We begin by considering a 2-dimensional simulation space and calculating the number of harassments for a small population of animals by each of the methods. The simulation space is divided into two depth bins and two range bins, as shown in Fig. 2. We assume that an underwater sound source has a source level (SL, in dB re: 1 µPa) sufficient to produce a sound field with an SPL of 195 dB inside a surface duct (top depth bin in Fig. 2). Below the surface duct (bottom depth bin in Fig. 1 the SPL is 120 dB.   The sonar emits 2 pings, each with duration of 0.49 seconds. Thus, the total SEL is just below 195 dB and we do not have to consider harassment due to the onset of TTS. Two animats are in the first range bin during the first ping and they are both in the second range bin during the second ping.   However, between pings, the second animat moves down below the surface duct.
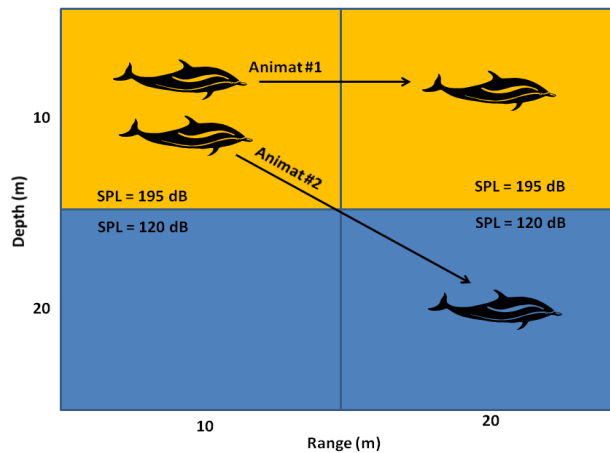
Figure 2: Illustration of the dive path for two animats in a simple 2 dimensional ocean environment containing a surface duct (shown in orange). The animat method considers both animats to be harassed due to their initial exposure to an SPL of 195 dB. For the static distribution method the space is divided into 4 quadrants; 2 range bins and 2 depth bins.

According to the animat method, both animats experienced a maximum SPL of 195 dB at some point in the simulation. Applying the risk function to this maximum SPL we find there is a 100% chance that animat #1 will be harassed (during either the first or second ping). Likewise, from the risk function, there is a 100% chance that animat #2 will be harassed (due to the first ping). Thus, a total of 2 harassments are predicted to occur as a result of the scenario.

In the static distribution method the total number of animats is first distributed among the range bins. Since, there are two animats in the simulation space and two range bins; we will have on average 1 animat per range bin. Next, we consider the animal depth distribution: the animats are 75% in the top depth bin (surface duct) and 25% in the lower depth bin (below the surface duct). There are two range bins so in each the depth distribution is 75% in the surface duct and 25% below (or 0.75 of an animal in the duct and 0.25 below for each range bin). The chosen sound level for this example is simple since in the surface duct the probability of a take is 1 and below is 0. Therefore the number of takes is 0.75 times a probability of 1 or .75 takes. This is multiplied by the two range bins to give a total of 1.5 takes for this environment as compared to 2 takes for the animat method.

Case 1: Uniform Surface Duct
The first case is used to illustrate the two methodologies in a less contrived environment than the previous example. This three-dimensional box ocean environment extends 100 km x 100 km with a depth of 1 km. Four different dive patterns are considered and the differences between the static distribution and animat methods are evaluated. This first simulation is extremely simplified but is instructive to show how large differences in the results of the methodologies are possible.

For this simplified simulation the surface duct extends down to 100 m. The SPL within the duct is 173 dB everywhere in the duct, so that after 120 pings the total SEL is 194 dB (which is below the threshold for TTS). Below the surface duct, the SPL is 119 dB and (from the risk function) there can be no harassments. The SPL in depth and range is shown in Figure 3.

One hundred animats were distributed in the ocean environment and randomly distributed across the surface of this ocean environment with a distribution of 0.01 animats per square kilometer. The (horizontal) swim and (vertical) dive patterns are defined for each animat's coordinates and depth at 30 second intervals for 1 hour. For this simplified example, the dive pattern for all 100 animats was the same within a simulation, but the starting coordinates and horizontal swim pattern remained unique. Four different simulations are considered to demonstrate the resulting differences between the animat and static distribution methods. In each simulation, all 100 animats are given the same dive pattern. The four dive patterns are shown in Figure 4A and their corresponding depth histograms are shown in Figure 4B.
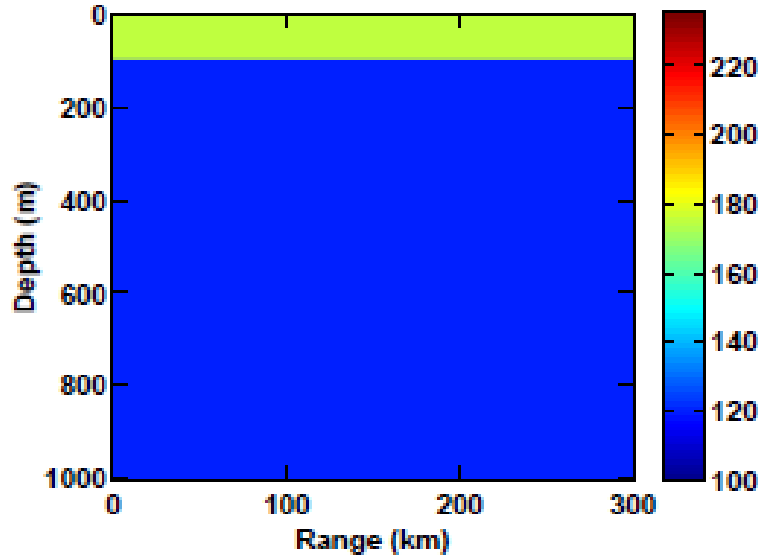
Figure 3. The sound pressure field (in SPL) from a source located at 0 km in range and 10 m depth and shows a uniform surface duct extending to 100 m depth. SPL values are mapped to the risk function for calculation of harassments in both the animat and static distribution analyses.
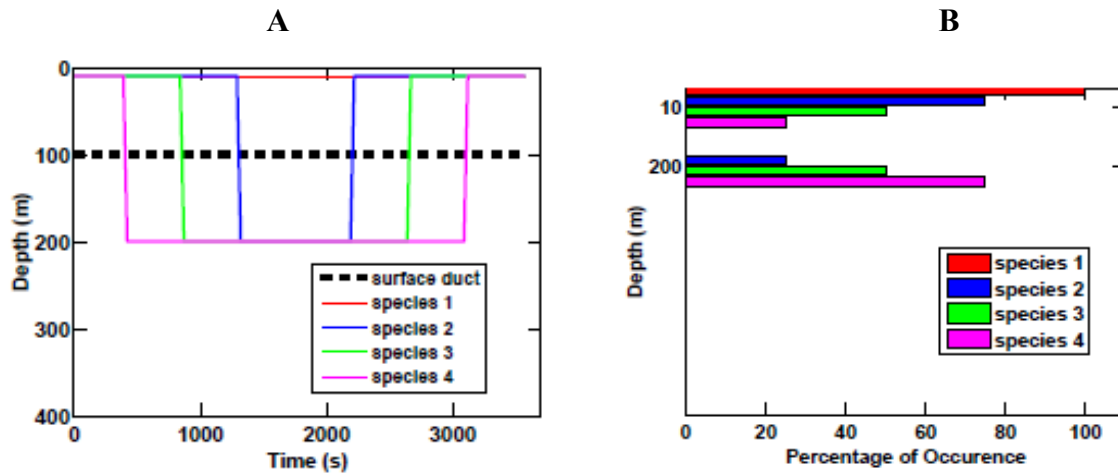
Figure 4. Panel A shows the simulated dive patterns for four artificial species in a surface duct used in the animat method. Species 1, 2, 3 and 4 stay within the duct (above 100 meters) 100, 75, 50 and 25% of the time, respectively, resulting in the depth histogram shown in panel B. The depth histograms are used in the static distribution method.

Each animat the coordinates and depths are extracted from the simulation and the maximum SPL corresponding to the overall dive profile is determined. The maximum received SPL value is applied to the risk function to find the "risk" of that animat being harassed. From Figure 4A it is apparent that in each of the four simulations, each of the 100 animats will be inside the surface duct at some point

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along its track, so each animat will receive an exposure of 173 dB SPL at least once during the simulation. Therefore, according to the risk function there is an 86.1% chance of each animat being harassed. Since there are 100 animats in the simulation the model arrives at a total of 86.10 harassments for each of the four simulations.

For the static distribution analysis, the 100 km x 100 km ocean surface is divided into 500 m x 500 m cells for a total of 40,000 cells. The model then applies the same animat distribution of 0.01 animats/km^2 to each of the cells (which have an area of 0.25 km^2) to get 0.0025 animats per cell. In the column below each cell, the 0.0025 animats are distributed according to the depth histogram for the corresponding scenario in Figure 4B. For each column in this ocean, the SPL value at each depth is applied to the risk function to find the proportion of animals harassed at each depth. The proportion is applied to the population distribution to arrive at the number of harassments for every column. Summing all of the harassments from all of the columns gives the total number of harassments in the simulation space. The results are listed in Table 1 for comparison with the animat method.

Notice that in each case, the static distribution results are reduced from the animat results by the same percentage of time that the animats spend below the surface duct from the depth histograms in Figure 4B. This is because the static distribution method assumes that some percentage of animats remain below the duct for the entire duration of the simulation, while others are exposed to sound in the duct for the whole simulation period. The animat method more accurately accounts for each animat's exposure history as it travels in and out of the surface duct. Also, note that the results of the two methods are virtually identical for species 1. This is because its dive pattern does change in time. Therefore, it is possible for the two methods to agree in some scenarios. The 2% difference in this case was due to the spatial sampling of the animats. Smaller vertical bin sizes would lead to increased accuracy.

Table 1: Number of harassments for simulated dive patterns. The number of harassments in the static distribution method is reduced by the percentage of time the animats are below the surface duct shown in Figure 4A. The number of harassments in the animat method remains the same for all species because they all experience a max SPL of 173 dB (re: 1 µPa) at some point during their dive track.

Species	Animat Method	Static Dist. Method	Percent Difference
1	86.10	87.82	2.01 %
2	86.10	65.87	23.49 %
3	86.10	43.91	49.00 %
4	86.10	21.96	74.50 %

Case 2: AUTEC Sound Speed Profile
Next, we consider the same box ocean as Case 1 but with a realistic sound speed profile taken from a measurement at the AUTEC Navy range. For this scenario, Bellhop was used to calculate the incoherent TL from a 235 dB source with 5 m sampling increments in both depth and range. Marine mammal movements were simulated using 3MB. Two different species were evaluated independently. First, the shallow-diving marine mammal was considered. One hundred animats with individually distinct dive patterns were exported from 3MB and evaluated by both the animat and static distribution methods as was done in case 1, above. Due to the randomized dive patterns of the animats in this

scenario the simulation was repeated 50 times, and the number of harassments was evaluated for each realization. The average number of harassments is plotted in Figure 5 where the error bars indicate the standard deviation of the cumulative realizations.

The ability to account for the variability in predictions resulting from variations in animat behavior is a capability of the animat approach, which is not readily apparent when implementing the static distribution method. Predictions of variability need not be limited to the standard deviation and other statistical approaches could be implemented. Whatever estimate of variability is used, the stabilization of the measure across multiple runs can be used to limit the number of times the Monte Carlo simulation must be carried out. Conversely, keeping record of the number of harassments across individual realizations permits the probability of maximum harassment events to be estimated. In combination with a measure of variability, both an estimate of the range of expected harassments and the potential for "spurious events" can be made. Such information would be beneficial to quantifying the uncertainty in impact estimates involving marine mammals and anthropogenic sound.
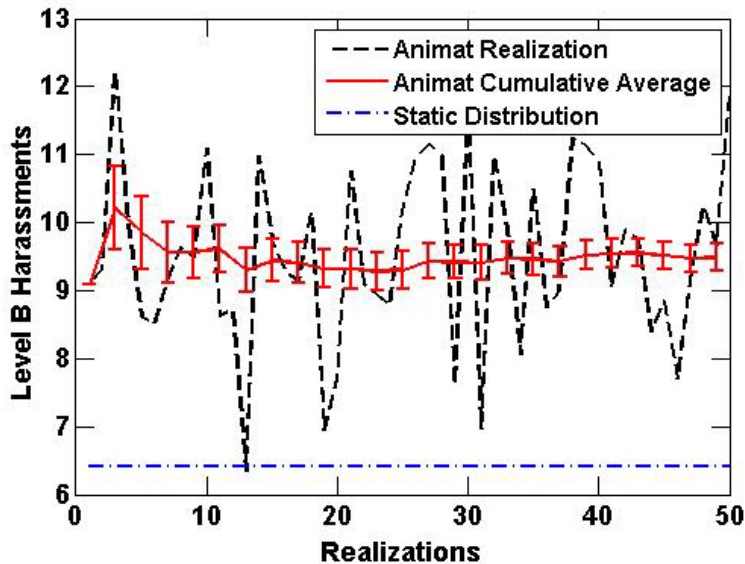
Figure 5. Number of harassments for a <u>shallow-diving species</u> in a 1 km deep ocean environment. After 50 realizations the animat method results in a mean of 9.54 harassments. Error bars indicate the standard deviation of the animat method. The static method arrives at a lower number of harassments.

For the static distribution method, the random dive patterns from all 5000 animats (100 animats x 50 realizations) were used to calculate the depth histogram. The animats were distributed into horizontal cells (500 m x 500 m) as in case 1, above, and then distributed into each column according to the depth histogram. The resulting number of harassments is plotted in Figure 5 for comparison with estimates obtained from the animat method. The number of harassments from each analysis method is also listed in Table 2.

Species	Animat Method	Static Distribution Method	Percent Difference
Shallow-diving	9.54	6.42	48.60 %
Deep-diving	8.67	3.42	153.51 %

Note that the static distribution method produced a result that was 48.60% lower than the mean harassment estimate obtained by the animat method. Although in at least one of the 50 realizations the take estimate was similar to that obtained with the static distribution method, the harassment estimate of the static distribution method consistently underestimated the harassment estimates obtained with the animat method. In the worst-case scenario, the estimate obtained via the static distribution method was half that estimated with the animat method.

A deep-diving animat species was also considered in this same ocean environment. Again, the animat method was repeated for 50 realizations. The final average after 50 realizations is listed in Table 2. Again, as in the shallow diving species, the static distribution method consistently underestimates the number of harassments estimated with the animat method. Similarly, the largest harassment estimate using the animat method is double that of the static distribution method.

Results on Adaptive Mesh Refinement of the simulation space
In this section we evaluate the risk as a function of depth and range using the Adaptive Mesh Refinement (AMR) method and compare the resulting number of takes with the conventional uniform grid approach. A deep ocean and a shallow ocean scenario were each used to compare the two methods. The maximum range required in each scenario is also considered by evaluating the takes as a function of range. Finally, we present a preliminary bathymetry analysis routine to place transects along bearings containing significant bathymetric features, and outline an AMR algorithm to sample the sloping bathymetry between these transects.

Case 1: Deep Ocean
The first case assumes the deep ocean environment described earlier, with convergence zones as shown in Fig. 1B. The analysis started with grid level 0 using a very coarse spacing of 320 meters (both in range and depth), and then reduced the spacing by ½ for each additional level of the analysis. Figure 6 illustrates the intermediate results in level 4 of the analysis routine. Figure 6A shows the calculated risk for a portion of the level 3 analysis area, from 0 to 4 km in range and 0 to 300 meters in depth with grid spacing of 40 meters. This risk result was then interpolated to a spacing of 20 meters in range and depth to give the risk shown in figure 6B. Next, the SPL was computed at each of these same points and the risk function was used to find the corresponding risk. The level 4 calculated risk is shown in Fig. 6C. Finally, the absolute value of the difference between the level 4 interpolated risk (Fig. 6B) and calculated risk (Fig. 6C) is calculated. Figure 6D shows the grid points where this difference exceeded a risk threshold of 0.1. A new grid is then formed around this subset of points and the process is repeated at level 5 with grid spacing of 10 meters. The process was continued until the grid spacing was reduced to 5 meters, at level 6. The final result is shown in figure 7A, where we note that the risk has diminished nearly to zero for ranges beyond 10 km.

Multiplying the risk in Fig. 7A by the population provides the number of takes at each point. The total number of takes for the entire simulation space was 30.504. The computations were performed on a Dell Optiplex 760 with Intel E8400 3GHz processor with 8 Gb of random access memory, and the total processing time for the AMR analysis was 30.1 seconds. For comparison, Bellhop was also used to calculate the SPL for the entire transect using a spacing of 5 meters, and the risk function was used to calculate the risk at each point. As in the AMR method, the risk was multiplied by the population at each point in the grid to get the total number of takes. The uniform grid approach resulted in 30.545 takes after a processing time of 443.8 seconds. The number of takes and processing times for each method are compared in Table 3.

The final risk distribution (Fig. 7A) suggests that calculating the SPL, risk and takes for points that are far from the source may not be an efficient use of computational resources. Figure 7B shows the distribution of takes as a function of range (solid line, left axis). We note that the number of takes near the source is nearly zero and then increases up to a maximum nearly 4km from the source, because the number of takes is the product of the population and risk. Although the SPL near the source is high, the population in the ring area (cylindrical volume) surrounding the source is very small and therefore the number of takes near the source is low. As the range increases the area of each ring surrounding the source also increases and the number of takes goes up. This trend continues until the decreasing SPL overtakes the increase in risk due to larger rings. Eventually, the risk declines to very low levels, causing the number of takes to also decline. Beyond 11 km the number of takes remains very low except near convergence zones (not shown) where it peaks slightly.
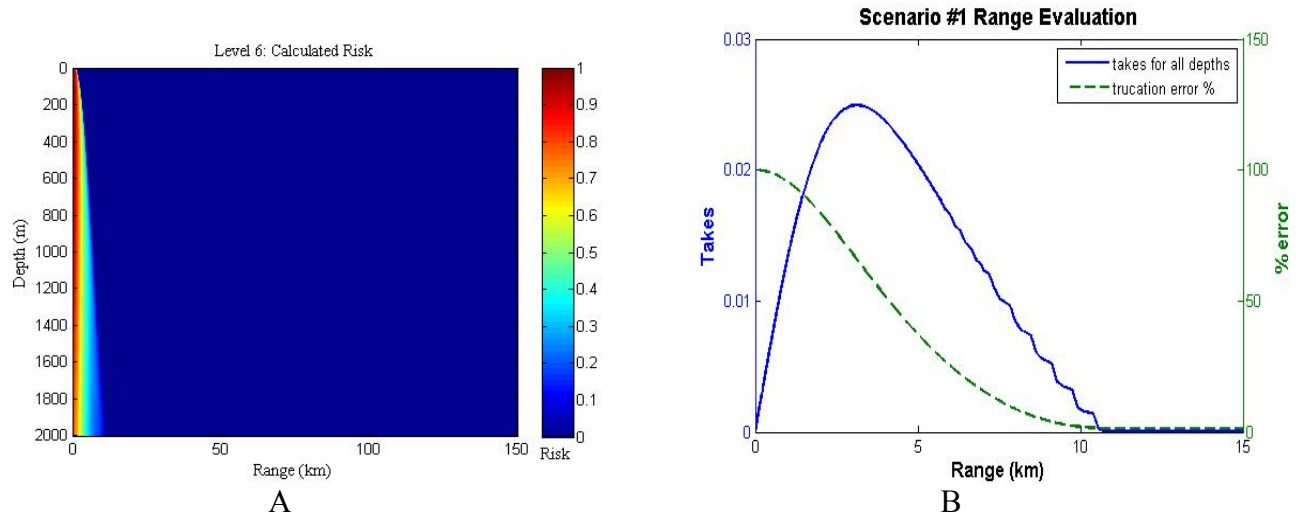
The error associated with truncating the range in the simulation is shown as the dashed line (right axis) in Fig. 7B. Note, that the simulation space could have been reduced from 150 km to 11 km with only a 2 percent error in the final result.
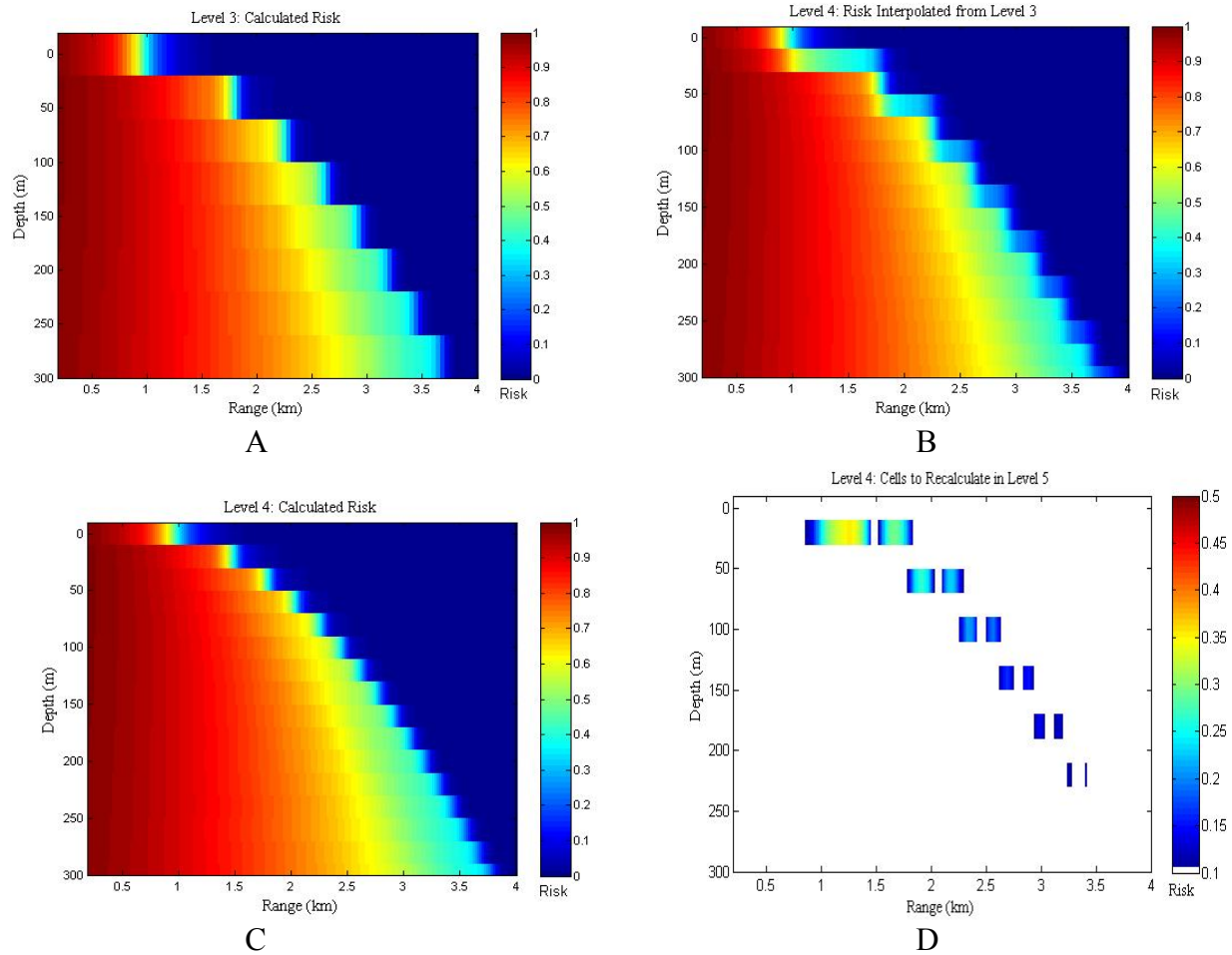
Figure 6. Panel A: The calculated risk for a portion of the level 3 analysis area with grid spacing of 40 meters. Panel B: The risk for a portion of the level 4 analysis area, interpolated from the level 3 analysis area, to a grid spacing of 20 meters. Panel C: The calculated risk for a portion of the level 4 analysis area using a grid spacing of 20 meters. Panel D: The absolute value of the difference between the interpolated risk (Panel B) and the calculated risk (Panel C). Only the grid points where the difference exceeded a risk threshold of 0.1 are shown. These points are then flagged and surrounded by a new smaller analysis area which is evaluated using a finer grid in level 5 of the analysis (not shown).

Table 3. Case 1 (Deep Ocean) comparison of the number of takes and processing times between the AMR method and the conventional uniform grid method. The AMR method arrived at a number of takes that was within 1% of the uniform grid result, 14 times faster than the conventional method.

| Case 1 (Deep Ocean)	AMR	Uniform Grid	% Difference
Total Takes	30.504	30.545	0.134 %
Time (sec)	30.1	443.8	93.2 %

A

B

Figure 7. Panel A: The risk values from case 1 (deep ocean) interpolated to a 5 meter grid. Panel B: The distribution of takes as a function of range (solid line, left axis). The risk at each point is multiplied by the population distribution (not shown) to arrive at the number of takes in the simulations space. The error associated with truncating the range in the simulation is also shown (dashed line, right axis). The simulation space could be reduced from 150 km to 11 km with only a 2% error in the final result.

Case 2: Shallow Ocean

The second case assumes the shallow ocean environment extending to a depth of 400 meters using a sound speed profile from AUTEC (Atlantic Undersea Test and Evaluation Center). The resulting surface duct is shown in Fig. 8A. The AMR method was used to compute the risk using a risk threshold of 1 percent. The risk was then multiplied by the population to provide the number of takes. The total number of takes for the entire simulation space was 99.809, and the total processing time for

the AMR analysis was 36.4 seconds. For comparison, Bellhop was again used to calculate the SPL for the entire transect using uniform spacing of 5 meters, and the risk function was used to calculate the risk at each point. The uniform grid approach resulted in 102.302 takes after a processing time of 82.3 seconds. The number of takes and processing times for case 2 are compared in Table 4.

Figure 8B shows the distribution of takes as a function of range (solid line, left axis). The error associated with truncating the range in the simulation is shown as the dashed line (right axis) in Fig. 8B. Note, that the simulation space could have been reduced from 150 km to 50 km with only a 2 percent error in the final result.


A   B
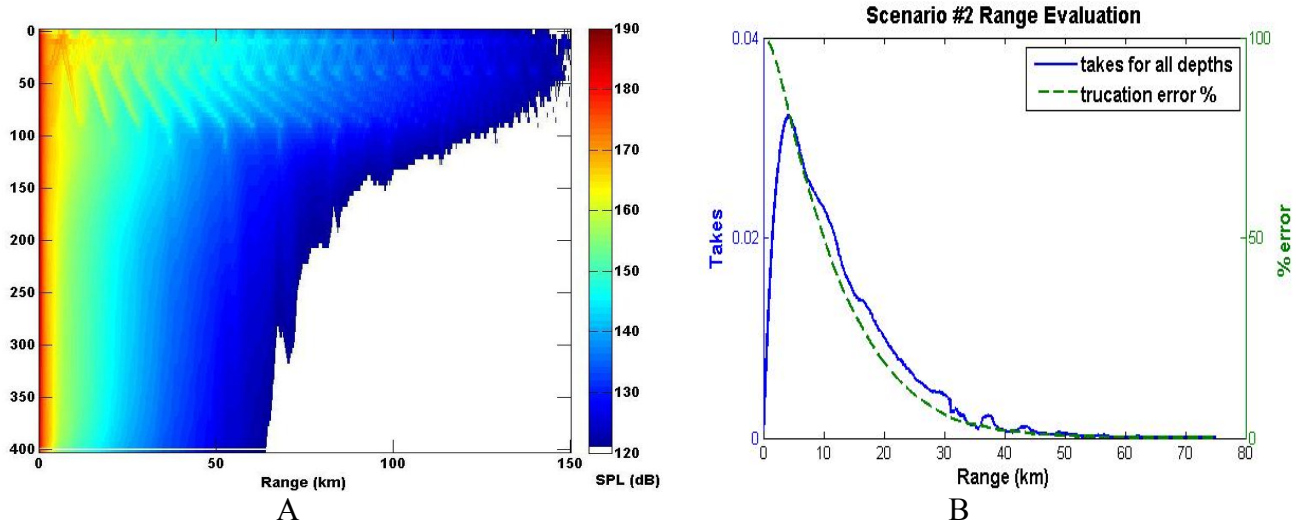
Figure 8. Panel A: Shallow ocean SPL values calculated with uniform 5 meter grid spacing. SPL below the basement level of the risk function (120 dB) are not shown. Panel B: The distribution of takes as a function of range (solid line, left axis). The risk at each point is multiplied by the population distribution (not shown) to arrive at the number of takes in the simulations space. The error associated with truncating the range in the simulation is also shown (dashed line, right axis). The simulation space could be reduced from 150 km to 50 km with only a 2% error in the final result.

Table 4. Case 2 (Shallow Ocean) comparison of the number of takes and processing times between the AMR method and the conventional uniform grid method. The AMR method arrived at a number of takes that was within 2.5% of the uniform grid result, more than 2 times faster than the conventional method.

| Case 2 (Shallow Ocean)	AMR	Uniform Grid	% Difference
Total Takes	99.809	102.302	2.44%
Time (sec)	36.356	82.325	55.84%

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Optimal Transect placement

The 2nd derivative of the bathymetry with respect to bearing, can be used to identify peaks and valleys in the bathymetry around a source location. As an example we consider a location in the Bahamas with the bathymetry shown in Figure 9A, where land is shown in red and deep ocean valleys are indicated by darker shades of blue. The absolute value of the second derivative of the bathymetry with respect to bearing is shown in figure 9B, where brighter colors represent either peaks or valleys. This provides an objective and automatic method to identify significant bathymetric features at the outset of a simulation. Transects can then be placed along bearing lines that contain such features and after SPL is calculated the risk can be interpolated in regions of sloping bathymetry.

A   B
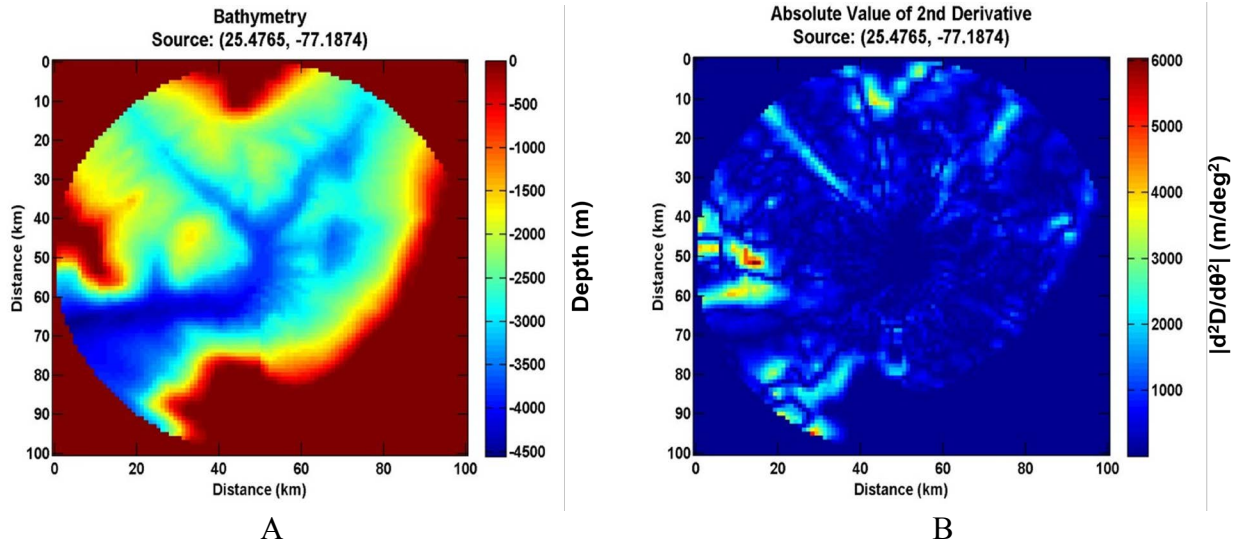
Figure 9. Panel A: The bathymetry for a location near the Bahamas. Panel B: The absolute value of the second derivative of the bathymetry with respect to bearing locates peaks and valleys in the bathymetry.

Results on One Navy Model Software Validation and Verification

A series of test cases are being developed to serve as sample cases for users of the ONM software. Each of these test cases was reviewed and repeated using MATLAB routines. That allows a simple way to test the implementation of codes in the ONM software while also providing users with test cases. Figure 10 shows and example test case being developed for a TL calculation for a transect done with the ONM software.

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Vertical SPL (dB re: 1 uPa), Transect #1, Bearing 210.0000 deg.
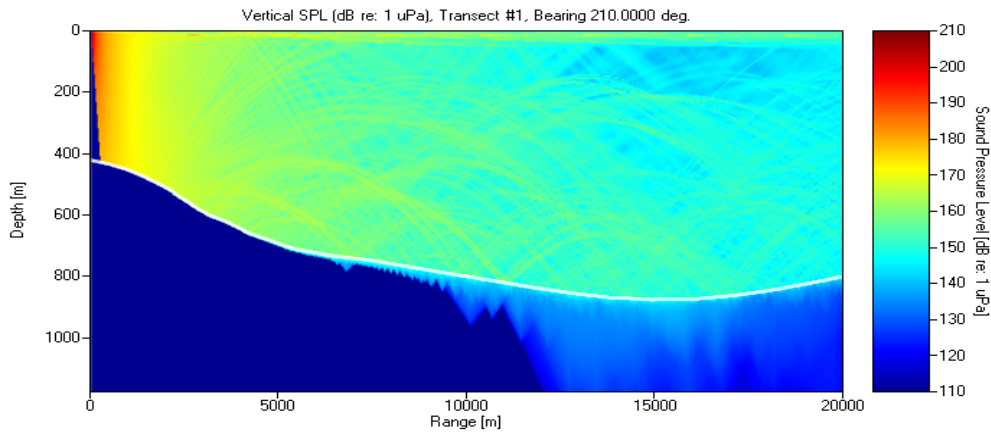
Figure 10. Test case developed for the ONM Software. Horizontal axis is range out to 20 km and the vertical axis is depth. The source uses typical settings for a mid-frequency active sonar without beam patterns.

IMPACT/APPLICATIONS

The analysis presented here demonstrate that the static distribution method of estimating Level B harassment of marine mammals consistently produces lower estimates than those produced by the animat method. Fundamentally, this occurs because the static distribution method forgoes the 4th dimension of the problem. It does not account for the occupancy of more than one sub-volume of ocean by individual animals. Marine mammals are dynamic in time and space and can traverse ranges and depths during military exercises or industrial activities that move them through multiple sub-volumes with differing levels of sound exposure. The animat method additionally offers some benefits to the quantification of uncertainty. First, the ability to calculate variability in harassment estimates can provide regulators with better understanding of the potential impact to marine species. Second, the ability to determine a probability of a "spurious event," in which many marine mammal harassments may occur, can be calculated. Collectively, these pieces of information will better inform the regulator as to the potential for impact to marine mammals resulting from the introduction of sound into the ocean by human-kind.

The analysis presented here on the Adaptive Mesh Refinement method indicates this has the potential to be used to improve computation time for sonar simulations. Evaluation of the resulting number of marine mammal takes indicates that limiting the maximum extent of the simulation space could save additional computational time. In addition, we address the need for an objective and automated method to distribute transects around the sound source.

Verification and validation efforts have been useful to insure the acoustic propagation algorithms in the ONM software are implemented correctly. The procedure developed at PSU has been useful in revealing implementation problems at the early stages so they can be easily addressed. Programmers at BU developing the ONM software are notified when these issues occur and resolve them before future versions are released.

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TRANSITIONS

None at this time.

RELATED PROJECTS

None at this time.

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